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# Hydrogen – a colour theory

Alexander Osojnik



In its pure, i.e. atomic form, hydrogen is the first element in the periodic table. Its element symbol is H, which stands for its Latin name, i.e. hydrogenium. With a mass fraction of about 70% of the total known mass, it is the most common element in the universe. In its pure form, it is so reactive that it rarely occurs on earth. It exists most frequently here in combination with other elements, e.g. in water (two hydrogen atoms paired with one oxygen atom) and hydrocarbons, especially crude oil and natural gas.

Scientists were producing hydrogen long before it was recognised as an element. As early as the 17$^{th}$ century, Théodore Turquet de Mayerne (around 1620) and Robert Boyle (around 1670) are said to have produced a gas they called oxyhydrogen (a mixture of gaseous hydrogen and oxygen) during experiments around the effects of acids on metals. In 1766, hydrogen was first discovered as an independent element by the English chemist and physicist Henry Cavendish. In 1783, Antoine Laurent de Lavoisier recognised that water was being produced when (oxyhydrogen) gas was being burnt and called the combustible gas "hydrogène" (Latin hydrogenium: "water-producing substance"), thus giving it its present name.

### The production of hydrogen

In 1838, the German chemist Christian Friedrich Schönbein discovered the principle of the fuel cell, which makes it possible to generate electricity from hydrogen and oxygen. Three years on, the English scientist Sir William Grove developed the first fuel cell model in his laboratory. A fuel cell converts the chemical energy of a fuel directly into electrical energy and heat. Most commonly, the term "fuel cell" would refer to a hydrogen-oxygen fuel cell, but some types of fuel cells can also use other fuels such as methanol, butane, or natural gas.

With the help of electrolysers, water can be broken down into hydrogen and oxygen. This process is called electrolysis (discovered in 1800) and is the reverse reaction of the aforementioned fuel cell. In the course of the energy transition, electrolysers will play an important role in the production of hydrogen.

### Why hydrogen?

Hydrogen is currently so popular because it has great potential to help achieving net zero emissions as a carbon-free fuel, electricity storage, or energy carrier. Complementary to other technologies such as renewable energies and biofuels, hydrogen could help to decarbonise or make these sectors climate-neutral, e.g. in the steel and fertiliser industry, in the petrochemical industry, in freight transport (on land and water) as well as in aviation and electricity generation or storage. However, this will only work if the production of hydrogen is climate-friendly and resource-friendly.

*…and what does this have to do with colours?*

Hydrogen is a colourless gas, so there is no visible difference between the different types of hydrogen. Depending on the source and the way it is produced, hydrogen is assigned a colour. However, we should point out that there is no universal naming or colour convention, i.e. the colour definitions may change over time or differ from country to country. Nevertheless, let's give it a try:

- **Black or brown hydrogen**

We speak of black or brown hydrogen when hydrogen ($H_2$) is produced by gasification (coal gasification) of hard coal (black) or lignite (brown). This environmentally very harmful process generates carbon dioxide ($CO_2$) and carbon monoxide (CO) as by-products, which are released into the atmosphere.

- **Grey hydrogen**

Grey hydrogen, currently the most common form of hydrogen (production), is obtained from fossil fuels, predominantly natural gas, through the process of steam reforming. Natural gas is thereby split into hydrogen and carbon dioxide, which is released as a waste product. Depending on the fuel and electricity mix, the production of one tonne of hydrogen produces around ten tonnes of $CO_2$.

- **Blue hydrogen**

This is also obtained from fossil fuels. Hydrogen is split off from methane ($CH_4$). The resulting carbon dioxide is captured and stored (carbon capture and storage (CCS)). The process is called low-carbon because the process of $CO_2$ capture and storage still releases greenhouse gases into the atmosphere. The potential environmental impact of $CO_2$ storage still needs further research. More and more companies are trying to use captured carbon (CCU). Blue hydrogen is seen as a bridge technology.

- **Green hydrogen**

This is produced by using "clean" electricity from renewable sources such as wind or solar energy in an electrolysis process (power-to-gas technology). In this process, water ($H_2O$) is broken down into hydrogen and oxygen ($O_2$) using electricity. This process is considered the only environmentally friendly, climate-neutral way to produce hydrogen. The share of green hydrogen in terms of total hydrogen production is currently still very limited. The greatest challenges for green hydrogen at the moment are the lack of sufficient renewable energies and the need for low electricity prices for renewable energies in order to increase the economic viability of production and competitiveness compared to hydrogen from fossil fuels.

- **Turquoise hydrogen**

Turquoise hydrogen, a relatively new entry in the hydrogen colour palette, is produced by a process called methane pyrolysis. In the absence of oxygen, the methane contained in natural gas is heated, producing hydrogen and, instead of gaseous $CO_2$, solid carbon. Solid carbon is more easily stored and can also be used in the chemical and electronics industries or in road construction. The process can be considered $CO_2$-neutral if the required high-temperature reactor is powered exclusively by renewable energy sources. This process requires significantly less energy than the production of green hydrogen. However, the feasibility of this process on an industrial scale must first be proven.

*It's getting even more confusing from here on in…*

- **Purple, pink, and red hydrogen**

With purple hydrogen, nuclear power and heat are used to break down the water. Pink hydrogen is when the electricity generated in a nuclear power plant is used for water electrolysis. Finally, red hydrogen is generated by using the heat energy of nuclear power plants, i.e., the high-temperature wastewater. More rarely, hydrogen produced by nuclear power is also called yellow hydrogen. No carbon dioxide is produced in the process itself.

- **Yellow hydrogen**

In the English literature, green hydrogen produced exclusively using solar power has recently been referred to as yellow hydrogen. In German-speaking countries, this is sometimes understood to mean hydrogen production by means of electrolysis with electricity from the currently available electricity mix, which can also come from gas-fired power plants, among other sources.

- **Orange hydrogen**

Hydrogen produced from bio-energy is defined as orange hydrogen. Bio-energy is understood to be carbon neutral energy produced from organic substances such as biomass, biofuel, biogas, and biomethane. These are obtained from waste and residues from agriculture, forestry, households and industry. These are obtained from waste and residual materials from agriculture, forestry, households, and industry. The carbon that was bound in the organic materials is released back into the environment after use. The process can thus be rated as low-carbon at best.

- **Natural (also: white) hydrogen**

The term white hydrogen refers to hydrogen that occurs in natural environments, e.g. in the USA, Russia, and Mali. It can be extracted by fracking, much like for the exploitation of fossil fuels. No meaningful information is yet available on possible environmental impacts, exploration methods, or production potential.

### A look into the future?

Currently, the aforementioned separation of water into hydrogen and oxygen by means of electrolysis with electrical power from renewable sources, i.e., the production of green hydrogen, is considered the most environmentally friendly method.

However, research is not static and has, for example, for many years investigated into the direct use of sunlight to split water without the diversion via photovoltaic systems to generate electricity. This requires suitable catalysts, such as titanium dioxide. The process of "photocatalytic" splitting of water was discovered 50 years ago by the Japanese researchers Akira Fujishima and Kenichi Honda.

### Research progress

Even though work and research on this process has been going on for a relatively long time, it has not yet been possible to scale up efficiency to the point where hydrogen can be produced on an industrial level. Important steps in this direction have now been taken at the Vienna University of Technology. In this process, tiny inorganic clusters consisting of only a small number of atoms are anchored to titanium oxide, a light-absorbing substructure. The combination of the clusters and the selected semiconductor structure then lead to the desired behaviour, i.e. that the energy of the absorbed light in the titanium oxide gives rise to free-moving electrons and free-moving electrical charges that enable the atomic clusters precisely placed on the surface to facilitate the splitting of water into hydrogen and oxygen.

Current research efforts are going towards improving the exact structure in order to increase efficiency. Relatively inexpensive materials such as cobalt, tungsten, and oxygen, which are responsible for the oxidation of oxygen, as well as sulphur and molybdenum, which are particularly suitable for the production of hydrogen molecules, are used in the process. In the case of cobalt and tungsten, increased attention would again be required in the supply chain in any case, as these elements are mined in conflict and high-risk areas, among other places, where human rights violations have occurred repeatedly.

This article is part of the **ESGenius Letter** on the topic of the *Energy of the Future*. The other articles with information and insights on sustainable energy use can be found here.

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## Alexander Osojnik

Senior Research Analyst, Erste Asset Management